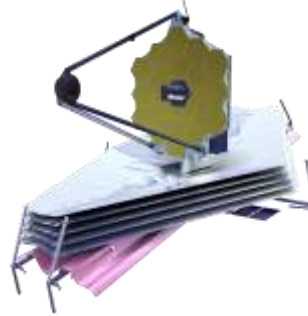




# 50+ years of NASA Mirror Technology Development:

from Hubble to JWST and Beyond



H. Philip Stahl, Ph.D.  
NASA



- WHERE IS THE U.S. GOING IN SPACE ?
- WHAT PROSPECTIVE NATIONAL GOALS REQUIRE NEW SPACE OPTICS ?
- SPACE ASTRONOMY
  - RESOLUTION
  - ULTRAVIOLET SPECTROSCOPY
  - INFRARED SPECTROSCOPY
- PLANETARY PROBES
  - LASER COMMUNICATION



## Presidential Vision

“... both optical and radio astronomy ... new fields of interest have been uncovered – notably in the high energy x-ray and gamma-ray regions. Astronomy is advancing rapidly at present, partly with the aid of observations from space, and a deeper understanding of the nature and structure of the Universe is emerging ... Astronomy has a far greater potential for advancement by the space program than any other branch of physics”.

## SPACE ASTRONOMY NEEDS

- LARGE - APERTURE    DIFFRACTION – LIMITED OPTICS
  - 2 METER
  - 3 METER
  - 10 METER
- FINE POINTING SYSTEMS    ( $< 1/100 \text{ SEC.}$ )
  - ALL WAVELENGTH TRANSFER LENS
  - PRECISE TORQUER GIMBALS
  - FREE FLOAT TELESCOPES
- SPACE MAINTAINABILITY
  - ALIGNMENT AND TUNE-UP
  - MODULAR SERVICING
  - SCIENTIFIC EXPERIMENTS    FLEXIBILITY

**Perkin-Elmer 1967**



## Presidential Vision

“... both optical and radio astronomy ... new fields of interest have been uncovered – notably in the high energy x-ray and gamma-ray regions. Astronomy is advancing rapidly at present, partly with the aid of observations from space, and a deeper understanding of the nature and structure of the Universe is emerging ... Astronomy has a far greater potential for advancement by the space program than any other branch of physics”.

### Space Task Group report to the President, September 1969

“A Long-Range Program in Space Astronomy”, position paper of the Astronomy Missions Board, Doyle, Robert O., Ed., Scientific and Technical Information Division Office of Technology Utilization, NASA, July 1969.



## 55 years ago in 1957 Space Astronomy Changed

On Oct 4, 1957 the world changed – Sputnik was placed in orbit around the Earth – and the Space Race was begun.



NASA formally opened for business on Oct. 1, 1958.



## State of Art before Sputnik

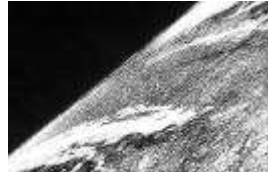
There are two important dates for American Space Astronomy before Sputnik:

10 Oct 1946, the first Ultraviolet Spectrum (to 210 nm) of the sun was obtained via a small film camera spectrograph mounted on a German V-2 Rocket launch by Von Braun's group at White Sands, NM.

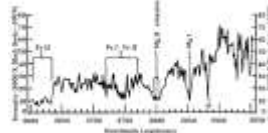
25 Sept 1957, the first launch of Stratoscope I.



US test launch of a Bumper V-2



First Image of Earth from Space



First UV Solar Spectra from Space



## Stratoscope I & II – 1957 to 1971

Stratoscope I (initial 25 Sept 1957)

Conceived by Martin Schwarzschild

Built by Perkin-Elmer

30 cm (12 inch) primary mirror

Film recording

Stratoscope II

Conceived by Martin Schwarzschild

Built by Perkin-Elmer

90 cm (36 inch) primary mirror

Payload 3,800 kg

25 km altitude

Film & Electronic



MSFC Launch September 9, 1971



## Space Astronomy

But,

Rocket Missions last for only a few minutes

Balloon Missions operate in the presence of Gravity and have a relatively 'soft' ride.

And neither are truly space.



## The Berkner Telegram

On July 4, 1958, Dr. Lloyd Berkner, Chair of the Space Science Board of the National Academy of Sciences, sent telegrams requesting suggestions for scientific experiments that may be performed by a satellite with a 50 kg capacity & fly in 2 years.

Proposals were due in 1 week. He got 200 responses.

This telegram and its responses lead to the OAO program.

Kick-off meeting was in 1959

Ames defined Requirements

GSFC was lead center

Grumman was Prime.



## Orbiting Astronomical Observatory (OAO)

From 1966 to 1972 NASA launched 4 OAO satellites

All had UV Science Experiments

OAO-I April 1966: Failed due to corona arching.

OAO-II Dec 1968 (on Atlas Centaur) to Jan 1973

OAO-B Nov 1970: Failed, Atlas Centaur didn't achieve orbit

OAO-C Aug 1972 to Feb 1981

Spacecraft	Experiment	Principal Investigators
OAO-II	University of Wisconsin Experiment	Dr. A. D. Code, Dr. T. E. Hoon's Univ. of Wis. Space Astronomy Laboratory
	Bombardier Astrophysical Observatory Experiment	Dr. F. Whipple, Dr. R. J. Davies, Smithsonian Astrophysical Observatory
OAO-B	GSFC Experiment	Dr. A. Hoggan II - Goddard Space Flight Center
OAO-C	Princeton University Experiment (Princeton Experiment Package)	Dr. Lyman Spitzer, Dr. John H. Egersman, Jr. - Princeton Univ.
	University College, London England	Prof. B. F. L. Boyd - University College, London



## OAO-C (Copernicus)

OAO-C had two Science Experiments

Princeton Experiment Package was a UV Spectrometer

81 cm Cassegrain telescope

Built by Perkin-Elmer for Princeton

Fine Guider achieved 0.1 arc-sec pointing

London Experiment X-Ray Package

3 small x-ray telescopes

5.5 cm<sup>2</sup> for 3 to 9 Angstroms

12 cm<sup>2</sup> for 6 to 18 Angstroms

23 cm<sup>2</sup> for > 44 Angstroms

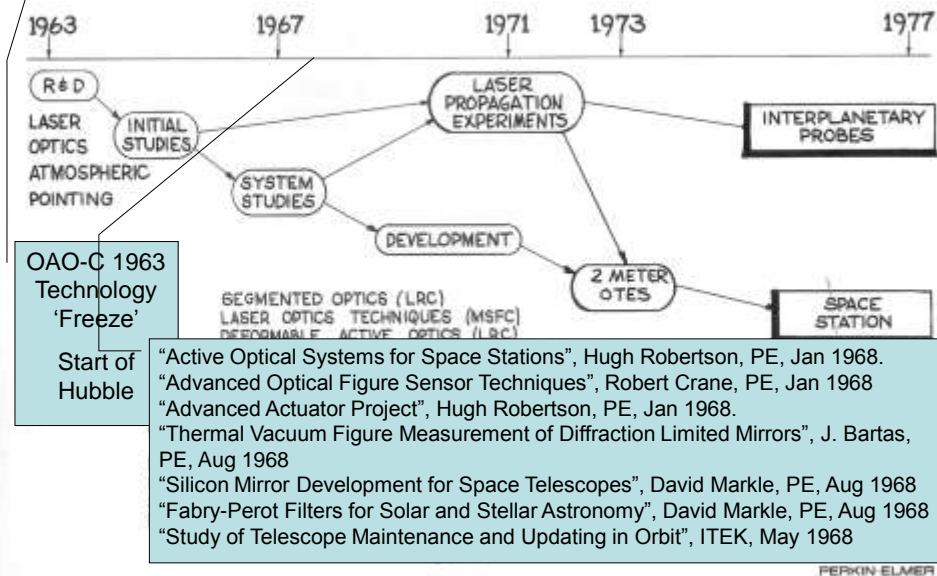
Deep parabolic grazing incidence mirrors

'first' piggy-back experiment

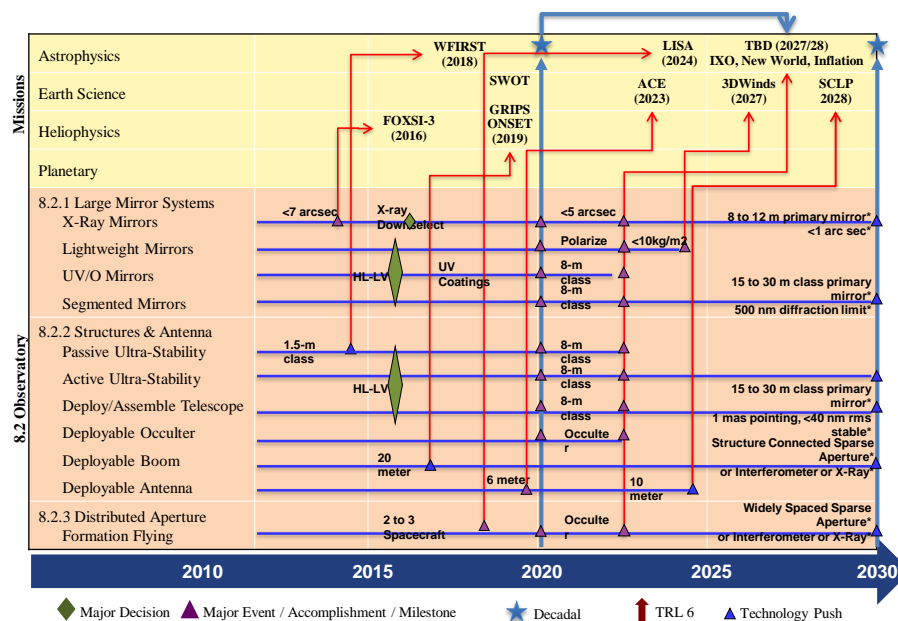
'first' x-ray telescopes in space?



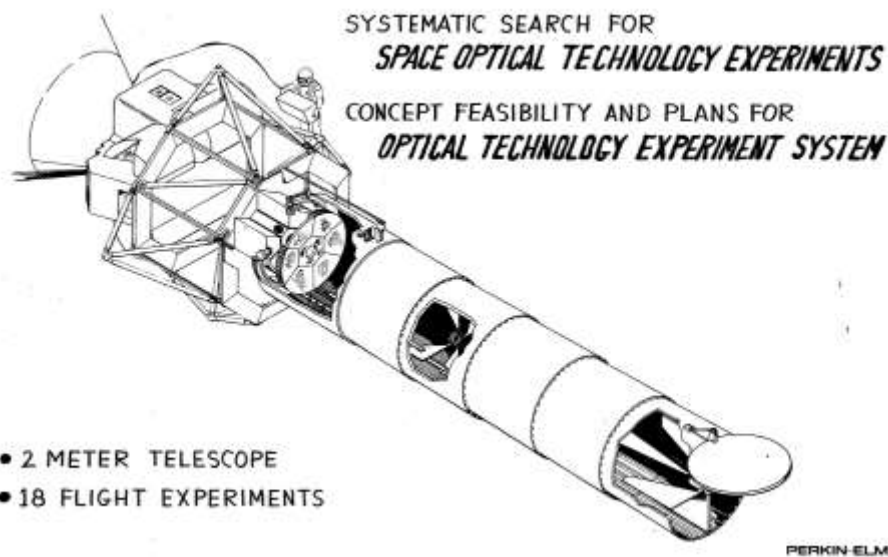
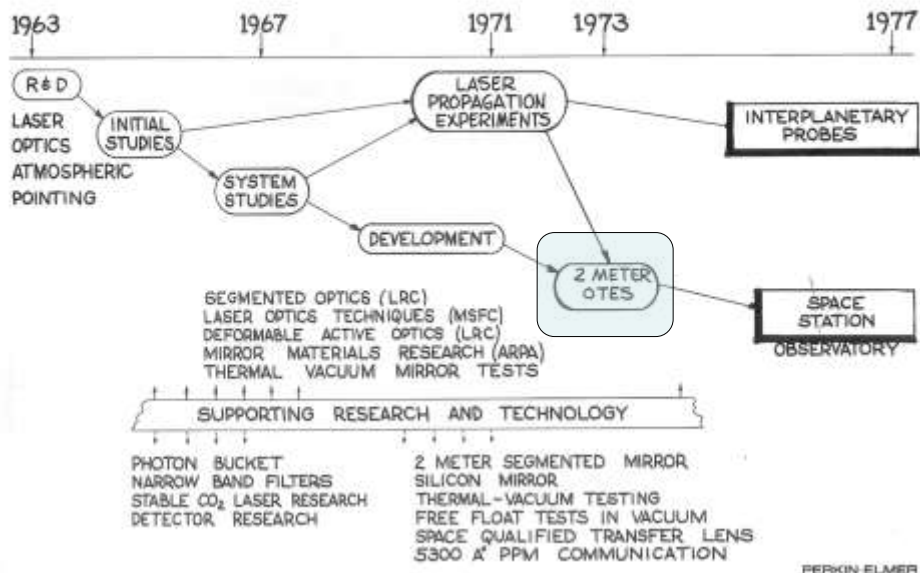
# NASA SPACE OPTICS TECHNOLOGY PLAN



## 8.2 Observatories Roadmap (OCT, 2011)



# NASA SPACE OPTICS TECHNOLOGY PLAN



Optical Technology Experiment System (OTES), PE, 1967  
Large Telescope Experiment Program (LTEP), PE 1969



## 2-METER OTES JUSTIFICATION

PROVIDE NASA WITH DATA FOR NATIONAL SPACE OBSERVATORY

- ORBITAL ALTITUDE DECISION DATA
  - DAYLIGHT ASTRONOMY
  - POINTING DISTURBANCES
  - THERMAL BALANCE
- MANNED SPACE ASTRONOMY TECHNIQUES
  - ERECTION
  - ALIGNMENT
  - MODIFICATION
  - MAINTENANCE
- PRIMARY MIRROR EVALUATION
  - ACTIVE OPTICS
    - SEGMENTED TESTS
    - DEFORMABLE TESTS
    - THERMAL TESTS
  - MATERIALS
    - QUARTZ
    - SILICON
    - CERVIT
    - BERYLIUM
- POINTING DEVELOPMENT
  - TRANSFER LENS
  - FREE FLOAT
  - FLEXURE GIMBALS
  - CLUSTER — AUTONOMOUS MODES

PERKIN-ELMER



“Large Telescope Experiment Program (LTEP)”, Perkin-Elmer, Aug 1969



## Large Telescope Experiment Program (LTEP)

Funded by the NASA Apollo Application Office

NASA is seriously searching out meaningful goals for after the most successful Saturn-Apollo missions to the lunar surface.

The new science and technologies of space labs and solar observatories are in the immediate future.

Data ... are critical for settling major questions in cosmology:

is the Universe infinite or not.”

“Large Telescope Experiment Program (LTEP) Executive Summary”, Alan Wissinger, April 1970



## National Astronomical Space Observatory (NASO)

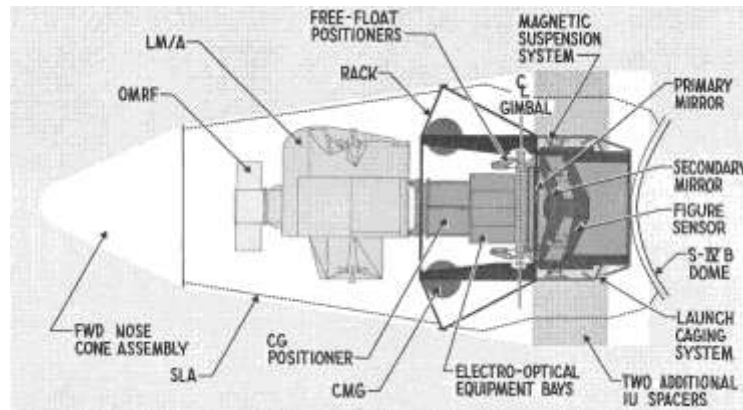
Initial Specifications:

- Operated at permanent space station
- Aperture of 3 to 5 meters
- Spectral Range from 80 nm to 1 micrometer
- Diffraction limit of at least 3 meters (0.006 arc-seconds) at 100 nm.
- Interchangeable experiment packages
- Life time of 10 years
- Field Coverage = 30 arc min
- Pointing Accuracy of 6 milli-arc second
- Thermal control - -80C +/- 5 C
- Mass (telescope only) = 5500 lb

“Large Telescope Experiment Program (LTEP) Executive Summary”, Alan Wissinger, April 1970



## Initial Launch Configuration for Saturn IB

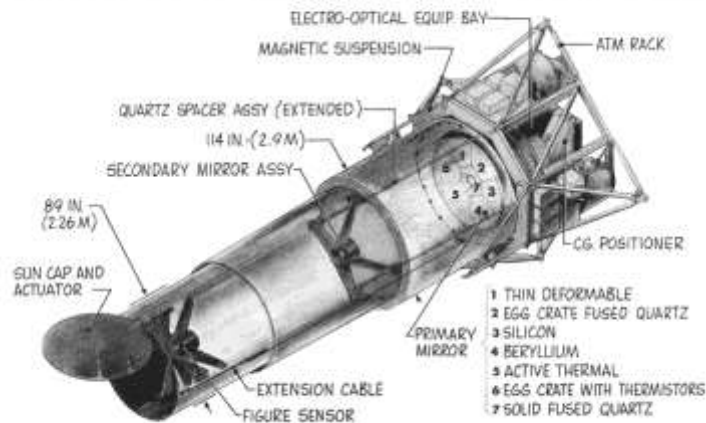


“Large Telescope Experiment Program (LTEP)”,  
Lockheed Missiles and Space Company, Jan 1970



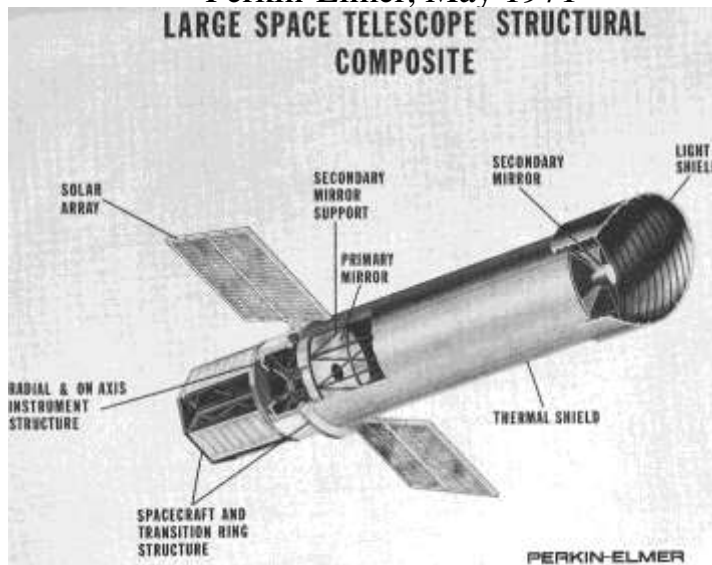
“Large Telescope Experiment Program (LTEP)”,  
Perkin-Elmer, Aug 1969

### LTEP-2-METER CONCEPT: EXTENDED CONFIGURATION





**“3-meter Configuration Study Final Briefing”,  
Perkin-Elmer, May 1971**



**Hubble Deployment April 25 1990**





## Next Generation Space Telescope Study

In 1996 (based on the 1989 Next Generation Space Telescope workshop and the 1996 HST & Beyond report) NASA initiated a feasibility study.

### Science Drivers

Near Infrared	1-5 microns (.6-30 extended)
Diffraction Limited	2 microns
Temperature range	30-60 Kelvin
Diameter	At least 4 meters ("HST and Beyond" report)

### Programmatic Drivers

25 % the cost of Hubble	Cost cap - \$500 million
25 % the weight of Hubble	Weight cap ~3,000 kg

### Baselines for OTA study

Atlas IIAS launch vehicle	<b>Low cost launch vehicle</b>
L2 orbit	Passively cool to 30-60 K
1000 kg OTA allocation	Launch vehicle driven



## Study Results ....

Science requires a 6 to 8 meter space telescope, diffraction limited at 2 micrometers and operating at below 50K.

### Segmented Primary Mirror

The only way to put an 8-meter telescope into a 4.5 meter fairing is to segment the primary mirror.

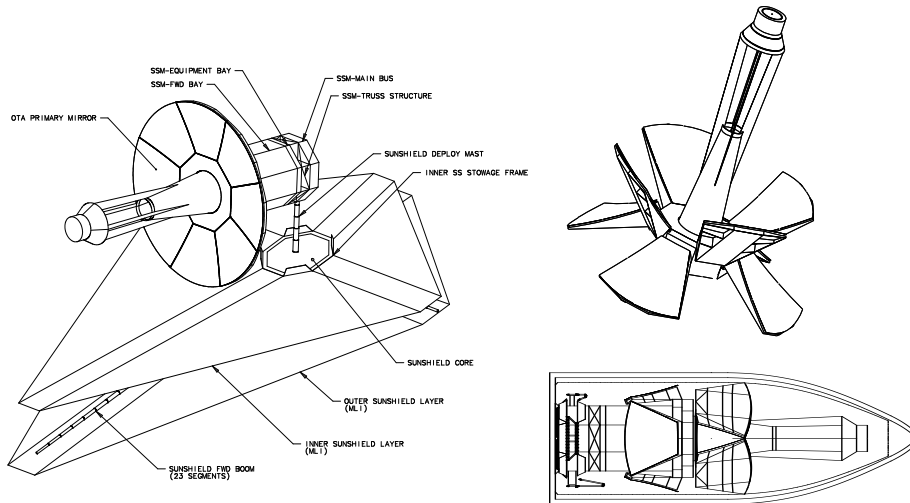
### Mass Constraint

Because of severe launch vehicle mass constraint, the primary mirror cannot weight more than 1000 kg for an areal density of  $< 20 \text{ kg/m}^2$

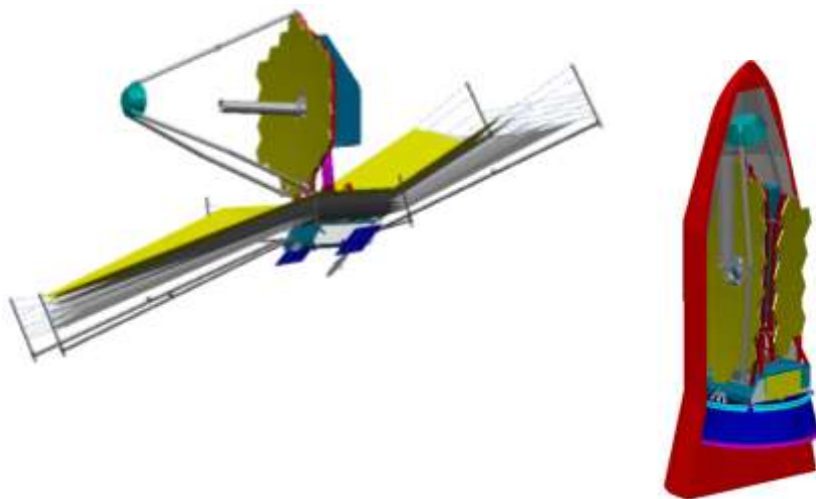
Such mirror technology did not exist



## Reference design – Lockheed / Raytheon



## Reference design – TRW/Ball





## LAMP Telescope - 1996



### Optical Specifications

- 4 meter diameter
- 10 meter radius of curvature
- 7 segments
- 17 mm facesheet
- 140 kg/m<sup>2</sup> areal density

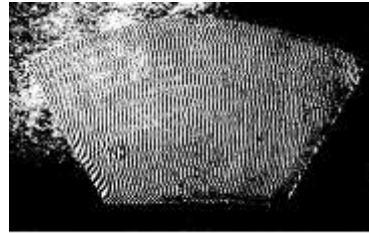


Fig. 12. Facesheet 3 final interferogram



## ALOT Telescope - 1994



### Optical Specifications

- 4 meter diameter
- Center & one Outer Petal
- 70 kg/m<sup>2</sup> areal density
- Active Figure and Piston Control
  - Eddy Current
  - Wavefront Sensor



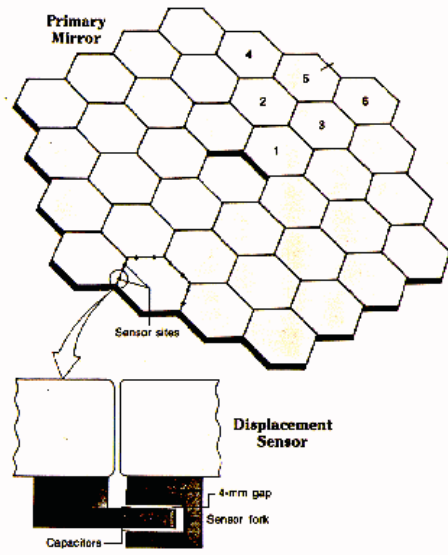
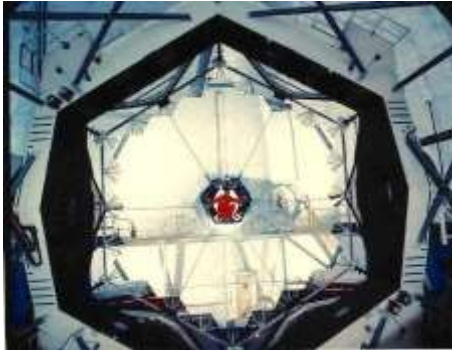
Phased two segment performance of 35 nm rms surface





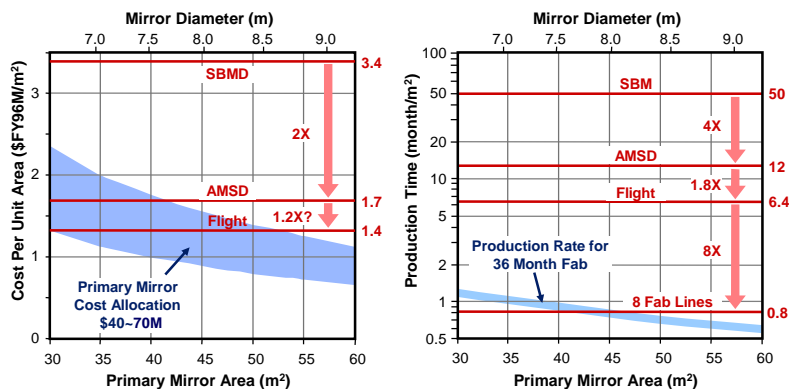
## Keck Telescope - 1992

10 meter diameter  
36 segments  
Capacitance Edge Sensors  
Diffraction Limited ~ 10 micrometers



## Programmatic Challenge of NGST

In 1996, the ability to affordably make NGST did not exist.  
Substantial reductions in ability to rapidly and cost effectively manufacture low areal density mirrors were required.







## Technical Challenges of NGST

Assessment of pre-1996 state of art indicated that necessary mirror technology (as demonstrated by existing space, ground and laboratory test bed telescopes) was at TRL-3

1996 JWST Optical System Requirements State of Art						
Parameter	JWST	Hubble	Spitzer	Keck	LAMP	Units
Aperture	8	2.4	0.85	10	4	meters
Segmented	Yes	No	No	36	7	Segments
Areal Density	20	180	28	2000	140	kg/m2
Diffraction Limit	2	0.5	6.5	10	Classified	micrometers
Operating Temp	<50	300	5	300	300	K
Environment	L2	LEO	Drift	Ground	Vacuum	Environment
Substrate	TBD	ULE Glass	I-70 Be	Zerodur	Zerodur	Material
Architecture	TBD	Passive	Passive	Hexapod	Adaptive	Control
First Light	TBD	1993	2003	1992	1996	First Light



## The Spitzer Space Telescope



LOCKHEED MARTIN

- ◆ Multi-purpose observatory cooled passively and with liquid-helium for astronomical observations in the infrared
- ◆ Launch in August 2003 for a 5+ year cryo mission in solar orbit, followed by 5-year "warm" mission
- ◆ Three instruments use state-of-the-art infrared detector arrays, 3-180um
- ◆ Provides a >100 fold increase in infrared capabilities over all previous space missions
- ◆ Completes NASA's Great Observatories
- ◆ An observatory for the community - 85% of observing time is allocated via annual Call for Proposal



Assembled SIRTf Observatory  
at  
Lockheed-Martin, Sunnyvale.  
Key Characteristics:  
Aperture – 85 cm  
Wavelength Range - 3-to-180um  
Telescope Temperature – 5.5K  
Mass – 870kg  
Height – 4m



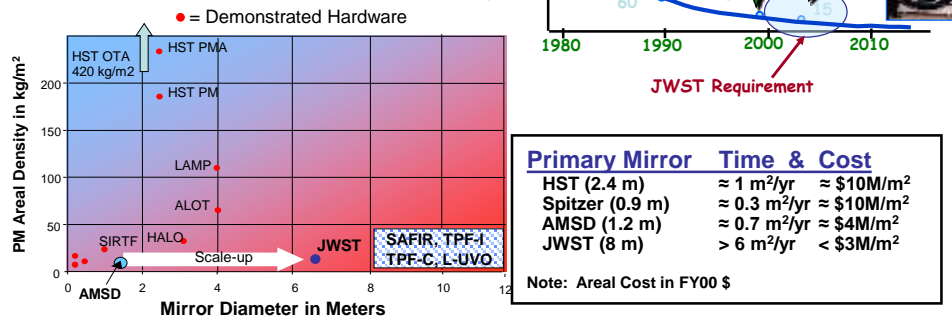
When I joined NASA in 1999, the overriding mantra for Space Telescopes was Areal Density, Cost & Schedule

Challenges for Space Telescopes:

Areal Density to enable up-mass for larger telescopes.

Cost & Schedule Reduction.

Are order of magnitude beyond 1996 SOA

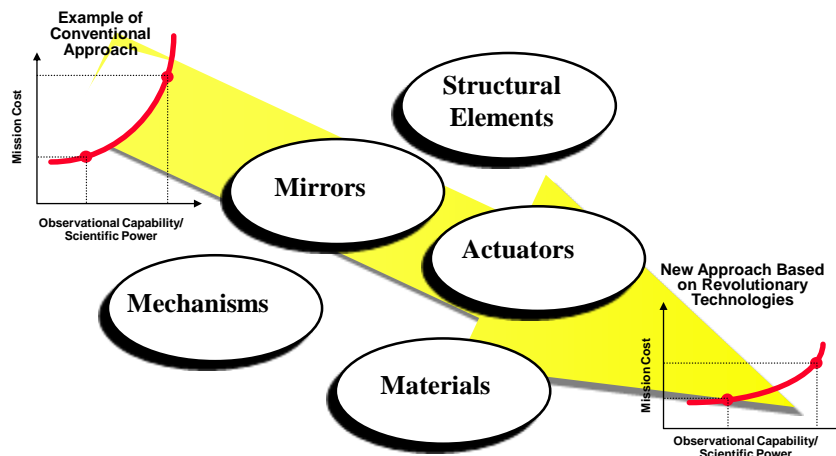


Although I've come to think that Stiffness and Areal Cost are more important



## The Role of Technology

An aggressive \$300M technology development program was initiated to change the cost paradigm for not only telescopes but also for detectors and instruments.





## Mirror Technology Development

A systematic \$40M+ development program was undertaken to build, test and operate in a relevant environment directly traceable prototypes or flight hardware:

- Sub-scale Beryllium Mirror Demonstrator (SBMD)
- NGST Mirror System Demonstrator (NMSD)
- Advanced Mirror System Demonstrator (AMSD)
- JWST Engineering Test Units (EDU)

Goal was to dramatically reduce cost, schedule, mass and risk for large-aperture space optical systems.

A critical element of the program was competition – competition between ideas and vendors resulted in:

- remarkably rapid TRL advance in the state of the art
- significant reductions in the manufacturing cost and schedule

It took 11 years to mature mirror technology from TRL 3 to 6.



## Enabling Technology

It is my personal assessment that there was 4 key Technological Breakthroughs which have enabled JWST:

- O-30 Beryllium (funded by AFRL)
- Incremental Improvements in Deterministic Optical Polishing
- Metrology Tools (funded by MSFC)
  - PhaseCAM Interferometer
  - Absolute Distance Meter
- Advanced Mirror System Demonstrator Project (AMSD)
  - funded by NASA, Air Force and NRO



## Substrate Material



### O-30 Beryllium enabled JWST



Spitzer used I-70 Beryllium while JWST uses O-30 Beryllium.

O-30 Beryllium (developed by Brush-Wellman for Air Force in late 1980's early 1990's) has significant technical advantages over I-70 (per Tom Parsonage)

Because O-30 is a spherical powder material:

- It has very uniform CTE distribution which results in a much smaller cryo-distortion and high cryo-stability
- It has a much higher packing density, thereby providing better shape control during HIP'ing which allows for the manufacture of larger blanks than what could be produced for Spitzer with I-70.

Because O-30 has a lower oxide content:

- It provides a surface quality unavailable to Spitzer, both in terms of RMS surface figure and also in scatter.

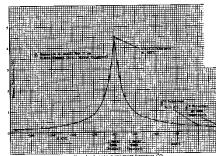
Ability to HIP meter class blanks demonstrated in late 1990's for VLT Secondary.

Full production capability in sufficient quantities for JWST on-line in 1999/2000.

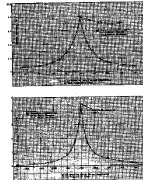


## 1960 Material Property Studies

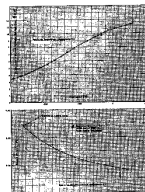
### PRIMARY MIRROR MATERIALS



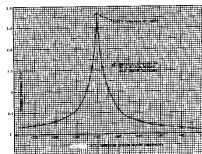
FUSED QUARTZ



CERVIT



BERYLLIUM



SILICON

PERKIN-ELMER



## Thermal Stability was Significant Concern

### THERMAL VACUUM TESTING OF SPACE MIRRORS



OTES  
EXPERIMENT 12

### THERMAL VACUUM TESTING OF SPACE MIRRORS



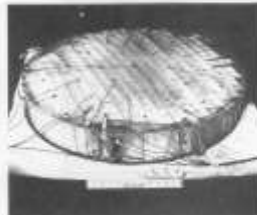
QUIESCENT

Mounting  
Point

HEATED

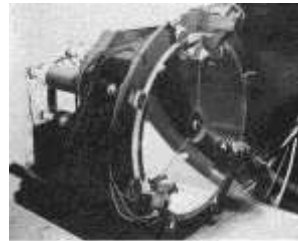
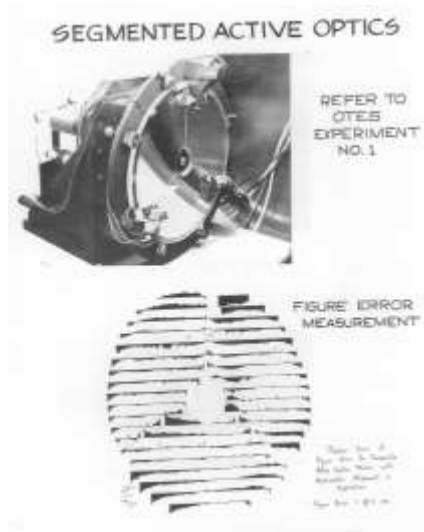


INSTRUMENTED  
OAO MIRROR

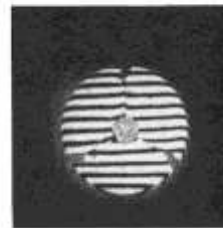




## Solution to Thermal Instability was Segmented Mirror



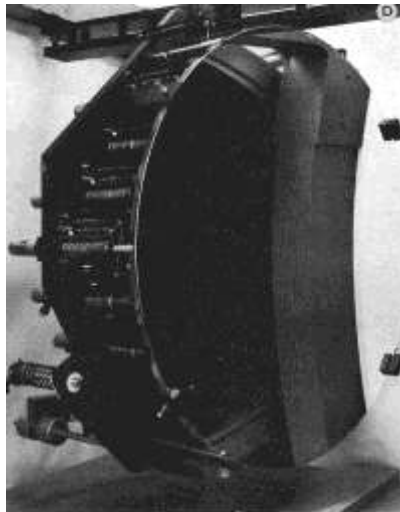
Segmented Mirror



Interferogram of Active Segmented Mirror  
Active Segmented Optics



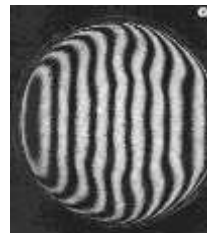
## Other Solution to Thermal Problem was Active Mirror



36 Inch Diameter Two Deformable Mirror



Two Deformable Mirror in Two-Deformable Mirror System



Two Deformable Mirror in Two-Deformable Mirror System



## **Final Solution was ...**

The final solution was to develop better mirror materials:

Cervit,  
ULE,  
Zerodur

which enabled a passive monolithic space telescope mirror

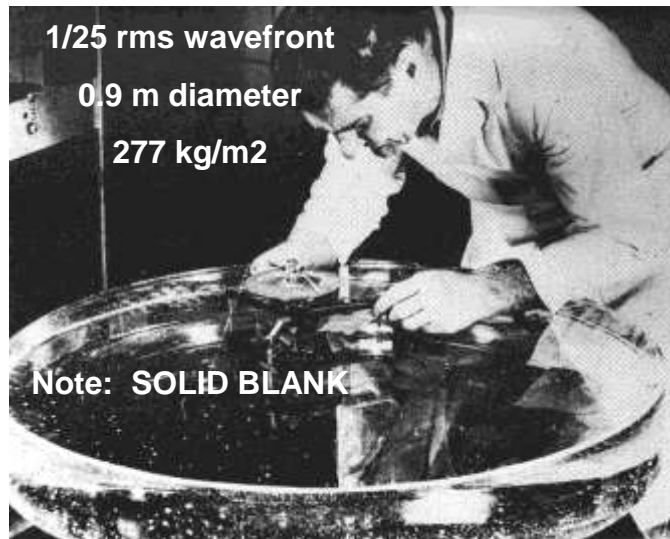


## **Mirrors:**

**Substrate Technology & Optical Fabrication**



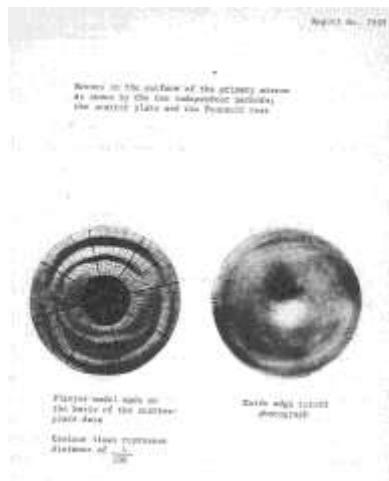
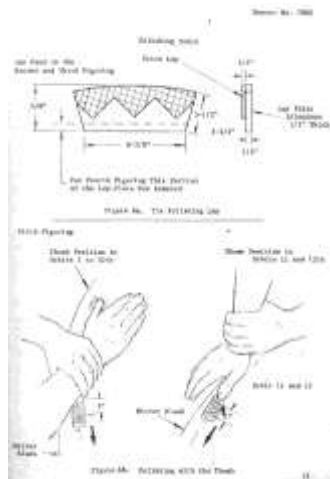
## Stratoscope II – Primary Mirror



36-Inch Diameter Stratoscope II Mirror  
Solid Fused Silica Blank T940 • Weight 400 Pounds



## Stratoscope II – Optical Fabrication



Classical Fabrication Techniques - Shaped Laps and Hand Figuring

“Test of the Primary and Secondary Mirrors for Stratoscope II”, Damant, Perkin-Elmer, Oct 1964.





## OA0-B Primary Mirror

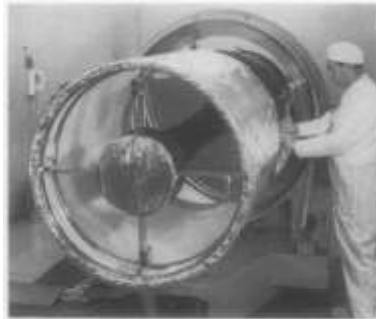


Fig. 3. View of the 36-inch GEP optical telescope.

State of Art (6:1 solid blank) fused silica mirror would have had a mass of 310 kg (680 lbs).

Beryllium (S200B) thin meniscus (25:1) substrate with electroless nickel overcoat was fabricated. Its mass was 57 kg (125 lb). Its stiffness minimized gravity sag

“The Goddard Experiment Pacakage – an Automated Space Telescope”, Mentz and Jackson,, Kollsman Instrument Corp, IEEE Transactions of Aerospace and Electronic Systems, Vol. 5, No. 2, pp. 253, March 1969



## OA0-C Primary Mirror



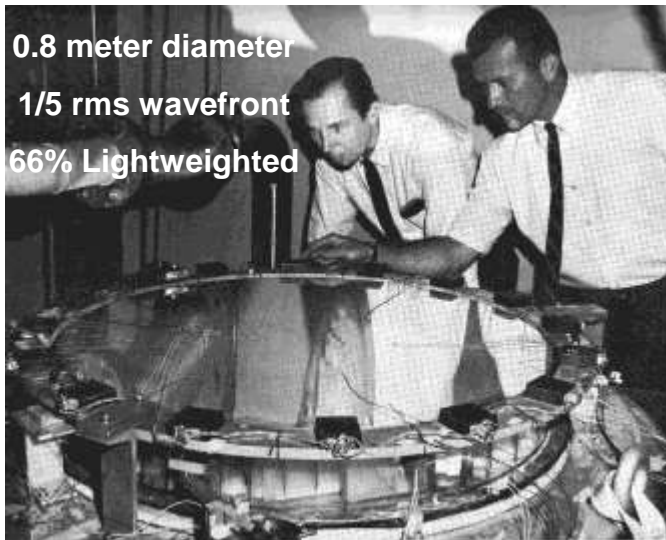
Fig. 4 Primary mirror before coating.

NASA is developing lightweight Egg-Crate Glass Mirror Substrates

“Princeton Experiment Package for OA0-C”, Norm Gundersen, Sylvania Electric Products Inc., J Spacecraft, Vol. 5, No. 4, pp. 383, April 1968.



## OA0-C Primary Mirror



0.8 meter diameter  
1/5 rms wavefront  
66% Lightweighted

32 Inch Diameter OA0-C Princeton University Eggcrate Mirror  
(Thermal/Deformation Test Instrumentation)



## Hubble Primary Mirror Fabrication 1979-81



Start of Small Tool Computer Controlled Polishing (I saw this)



## Spitzer (ITTT) PM Fabrication



## Spitzer PM Fabrication

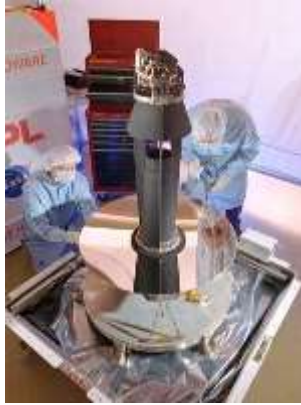


PM used Small Tool Computer Controlled Polishing

SM used Full Aperture Shaped Laps and Zonal Laps



## Spitzer Optical Telescope Assembly and Primary Mirror



## JWST Mirror Manufacturing Process

### Blank Fabrication



HIP Vessel being loading into chamber



Machining of Web Structure



Machining of Optical Surface



Completed Mirror Blank

### Polishing



### Mirror System Integration





## Mirror Fabrication at L-3 SSG-Tinsley



## Optical Testing





## Optical Testing

you cannot make what you cannot measure

In 1999, the NGST program had a problem.

To produce cryogenic mirrors of sufficient surface figure quality, it was necessary to test large-aperture long-radius mirrors at 30K in a cryogenic vacuum chamber with a high spatial resolution interferometer.

The state of the art was temporal shift phase-measuring interferometers, e.g. Zygo GPI and Wyko.

**Spatial resolution was acceptable, but mechanical vibration made temporal phase-modulation impossible.**

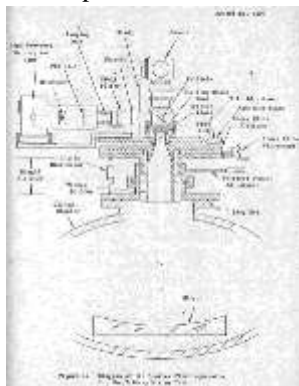
But this problem is nothing new .....



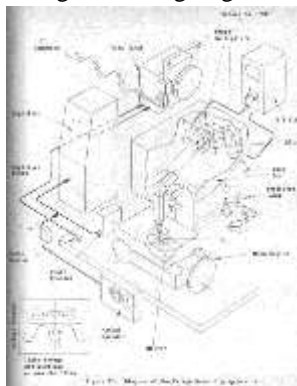
## Stratoscope II – Optical Testing

One solution is common path interferometry

Scatterplate Interferometer



Fringe Scanning Digitizer



(And, in grad school I thought scatterplate interferometer was a laboratory curiosity.)

Testing support from J.M. Burch, A. Offner, J.C. Buccini and J. Houston

OAOC also used scatter plate interferometry

“Test of the Primary and Secondary Mirrors for Stratoscope II”, Damant, Perkin-Elmer, Oct 1964.



## Hubble Testing

Another solution is short exposure time.

Hubble optical testing (at both Perkin-Elmer and Kodak) was performed with custom interferometers taking dozens of film images which were digitized to produce a surface map.

- Camera Shutter Speed ‘freezes’ vibration/turbulence
- PE used custom micro-densitometer and Kodak manually digitized
- PE tested in the vertical ‘Ice-Cream Cone’ vacuum chamber

Even in the 1990’s when I worked at PE (then Hughes) I would hand digitize meter class prints of interferograms.



## Hubble Primary Mirror Optical Testing

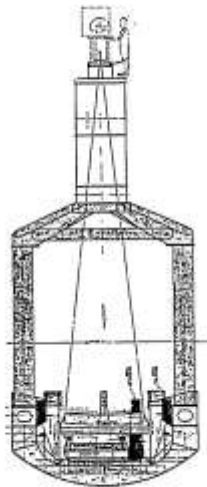


Figure 2. Primary mirror test configuration.

Montagnino, Lucian A., "Test and evaluation of the Hubble Space Telescope 2.4 meter primary mirror", SPIE Vol. 571, pp. 182, 1985.



## Hubble Interferogram Digitization & Analysis

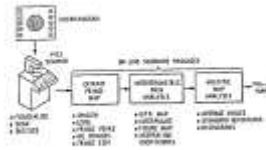


Figure 14. Interferogram analysis facility.

1. 1.0000
2. 1.8137E-05 COS 0
3. 1.9137E-05 SIN 0
4. 1.8867E-05 - 0.26320
5. 3.3375E-05 COS 20
6. 3.2375E-05 SIN 20
7. 8.3130E-05 - 0.47148E-05
8. 8.3130E-05 - 0.47148E-05
9. 3.4932E-05 COS 30
10. 3.4932E-05 COS 30
11. 16.318E-05 - 1.4930E-05 - 0.2020
12. 15.114E-05 - 0.7050E-05 COS 40
13. 15.114E-05 - 0.7050E-05 SIN 40
14. 3.1148E-05 COS 40
15. 3.1148E-05 SIN 40
16. 30.420E-05 - 1.1238E-05 - 0.11440E-05
17. 35.100E-05 - 1.7700E-05 - 0.11440E-05
18. 16.703E-05 - 0.8000E-05 COS 50
19. 16.703E-05 - 0.8000E-05 SIN 50
20. 0.5000E-05 COS 50
21. 0.5000E-05 SIN 50
22. 78.210E-05 - 1.0350E-05 - 0.5440E-05 - 0.0940
23. 108.23E-05 - 1.0350E-05 - 1.0350E-05 - 0.5440E-05 - 0.2770

Figure 16. Annular Zernike polynomials for 0.3 obscuration.

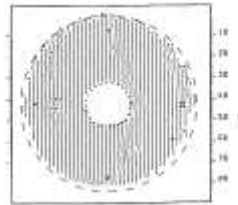


Figure 15. Fringe map.

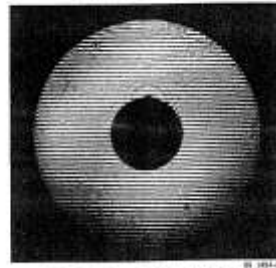


Figure 17. Interferogram of finished primary mirror masked to its clear aperture.

Montagnino, Lucian A., "Test and evaluation of the Hubble Space Telescope 2.4 meter primary mirror", SPIE Vol. 571, pp. 182, 1985.



## Spitzer Secondary Mirror Testing



Another solution is structurally connect interferometer and test.



Spitzer (ITTT) Secondary Mirror Hindle Sphere Test Configuration using a Zygo GPI with Remote PMR Head.





## PhaseCAM

At BRO, I designed, built and wrote the software for a 480 Hz common path phase-measuring Twyman-Green interferometer that was used to test all the Keck segments at ITEK.

As I prepared to leave Danbury for NASA, I was visiting Metrolaser where I saw a breadboard device taking phase-maps of a candle flame.

When I got to NASA I defined the specifications for and ordered the first PhaseCAM interferometer.

Today they are critical to JWST.



Tech Days 2001



## Mirror Technology Development Program





## Mirror Technology Development

### Systematic Study of Design Parameters

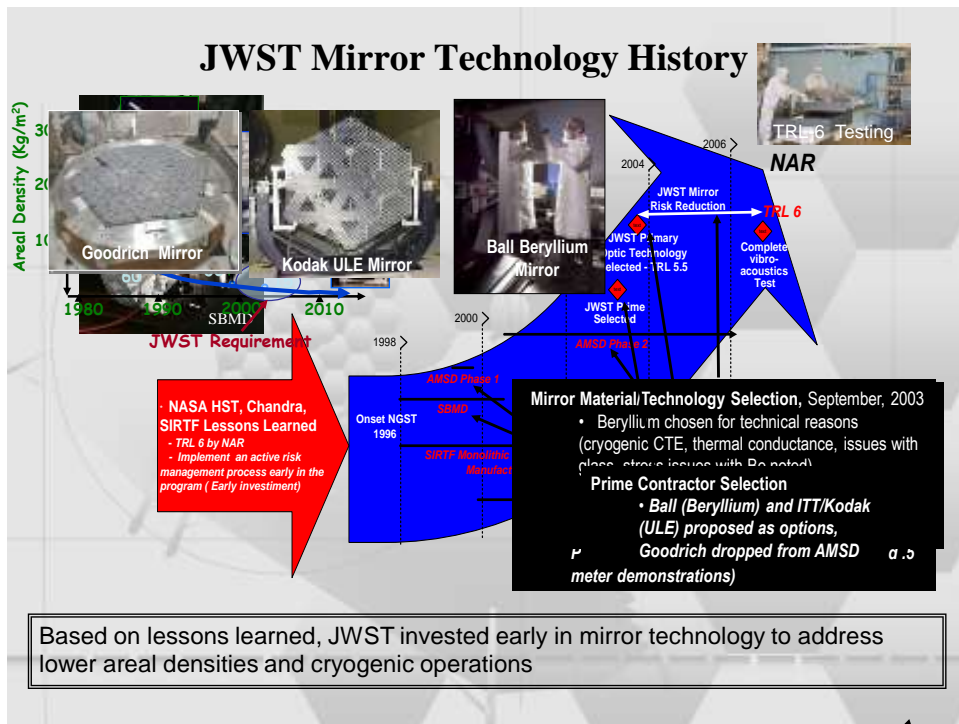
Item	SBMD	NMSD	AMSD
Form	Circle w Flat	Hex	Hex
Prescription	Sphere	Sphere	OAP
Diameter	>0.5 m	1.5 - 2 m	1.2 - 1.5 m
Areal Density	< 12+ kg/m <sup>2</sup>	<15 kg/m <sup>2</sup>	<15 kg/m <sup>2</sup>
Radius	20 m	15 m	10 m
PV Figure	160 nm	160/63 nm	250/100 nm
RMS Figure			50/25 nm
PV Mid (1-10 cm <sup>-1</sup> )	63 nm	63/32 nm	
RMS Finish	3/2 nm	2/1 nm	4 /2 nm



## Mirror Technology Development

### Wide Variety of Design Solutions were Studied

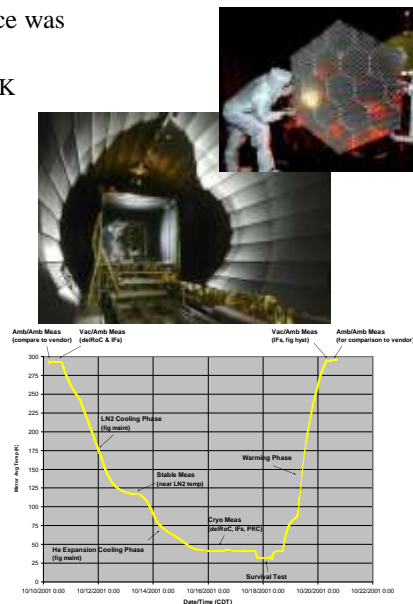
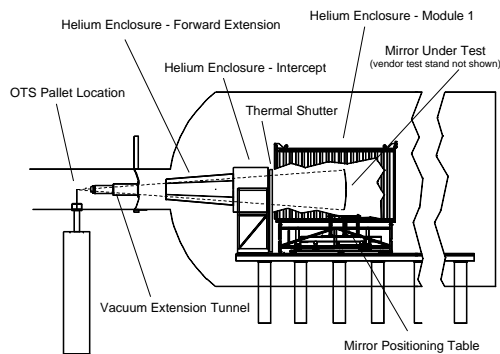
Item	SBMD	NMSD	AMSD
Substrate Material	Be (Ball)	Glass (UA) Hybrid (COI)	Be (Ball) ULE Glass (Kodak) Fused Silica (Goodrich)
Reaction Structure	Be	Composite Composite (all)	
Control Authority	Low	Low (COI) Low (Ball) High (UA)	Medium (Kodak) High (Goodrich)
Mounting	Linear Flexure	Bipods (COI) 166 Hard (UA)	4 Displacement (Ball) 16 Force (Kodak) 37 Bi/Ax-Flex (Goodrich)
Diameter	0.53 m	2 m (COI) 1.6 m (UA)	1.3 m (Goodrich) 1.38 m (Ball) 1.4 m (Kodak)
Areal Density	9.8+ kg/m <sup>2</sup>	13 kg/m <sup>2</sup>	15 kg/m <sup>2</sup>



## Performance Characterization

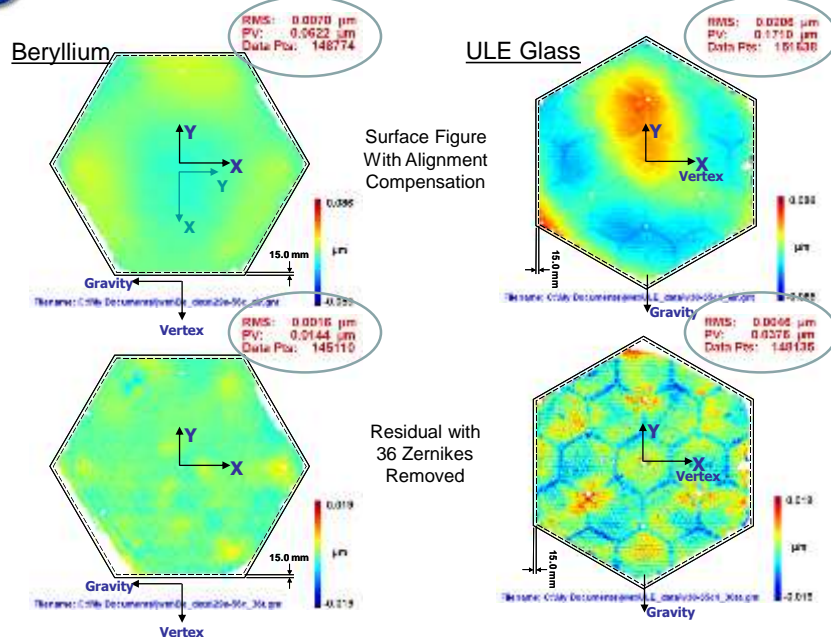
Ambient and Cryogenic Optical Performance was measured at XRCF.

Each mirror tested multiple times below 30K

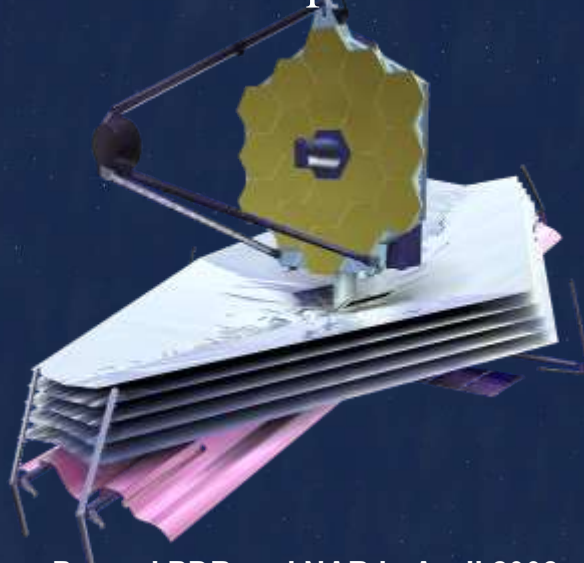




## AMDS Figure Change: 30-55K Operational Range



## James Webb Space Telescope



Passed PDR and NAR in April 2008

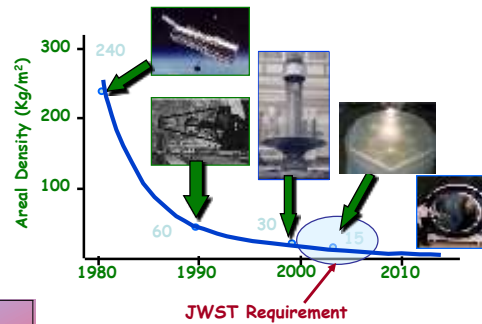
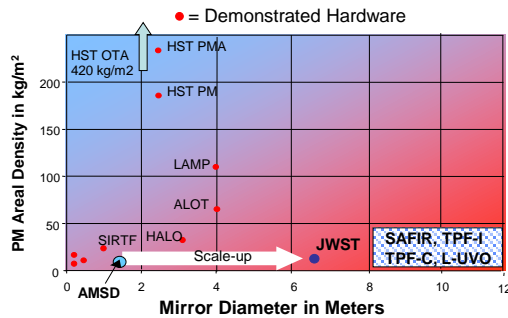


## Mirror Technology Development - 2000

Challenges for Space Telescopes:

Areal Density to enable up-mass  
for larger telescopes.

Cost & Schedule Reduction.



### Primary Mirror Time & Cost

HST (2.4 m)	$\approx 1 \text{ m}^2/\text{yr}$	$\approx \$10\text{M}/\text{m}^2$
Spitzer (0.9 m)	$\approx 0.3 \text{ m}^2/\text{yr}$	$\approx \$10\text{M}/\text{m}^2$
AMSD (1.2 m)	$\approx 0.7 \text{ m}^2/\text{yr}$	$\approx \$4\text{M}/\text{m}^2$
JWST (8 m)	$> 6 \text{ m}^2/\text{yr}$	$< \$3\text{M}/\text{m}^2$

Note: Areal Cost in FY00 \$

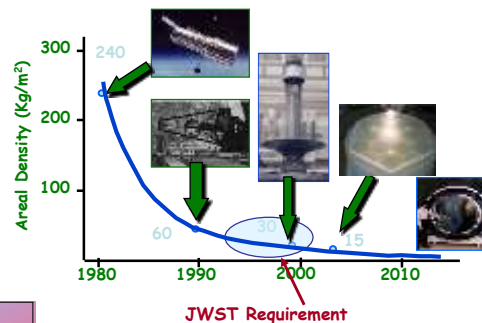
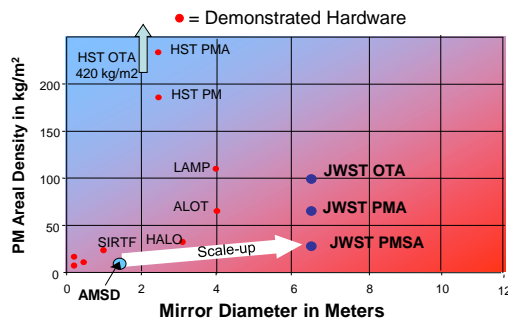


## Mirror Technology Development 2010

Lessons Learned

Mirror Stiffness (mass) is required to  
survive launch loads.

Cost & Schedule Improvements are  
holding but need another 10X  
reduction for even larger telescopes



### Primary Mirror Time & Cost

HST (2.4 m)	$\approx 1 \text{ m}^2/\text{yr}$	$\approx \$12\text{M}/\text{m}^2$
Spitzer (0.9 m)	$\approx 0.3 \text{ m}^2/\text{yr}$	$\approx \$12\text{M}/\text{m}^2$
AMSD (1.2 m)	$\approx 0.7 \text{ m}^2/\text{yr}$	$\approx \$5\text{M}/\text{m}^2$
JWST (6.5 m)	$\approx 5 \text{ m}^2/\text{yr}$	$\approx \$6\text{M}/\text{m}^2$

Note: Areal Cost in FY10 \$



## Chickens, Eggs and the Future

**Was Shuttle designed to launch  
Great Observatories or were Great  
Observatories designed to be  
launched by the shuttle?**



“Large Telescope Experiment Program (LTEP) Executive Summary”,  
Alan Wissinger, April 1970





## Design Synergy

### Shuttle

Payload Bay designed to deploy, retrieve and service spacecraft  
Robotic Arm for capturing and repairing satellites.

### Mission Spacecraft

Spacecraft designed to be approached, retrieved, and repaired  
Generic Shuttle-based carriers to berth and service on-orbit



Chandra and Spitzer were originally intended to be serviceable.



## Great Observatories designed for Shuttle

Hubble, Compton and Chandra were specifically designed to match Space Shuttle's payload volume and mass capacities.

	Launch	Payload Mass	Payload Volume
Space Shuttle Capabilities		25,061 kg (max at 185 km) 16,000 kg (max at 590 km)	4.6 m x 18.3 m
Hubble Space Telescope	1990	11,110 kg (at 590 km)	4.3 m x 13.2 m
Compton Gamma Ray Observatory	1991	17,000 kg (at 450 km)	
Chandra X-Ray Telescope (and Inertial Upper Stage)	2000	22,800 kg (at 185 km)	4.3 m x 17.4 m
Spitzer was originally Shuttle IR Telescope Facility (SIRTF)			

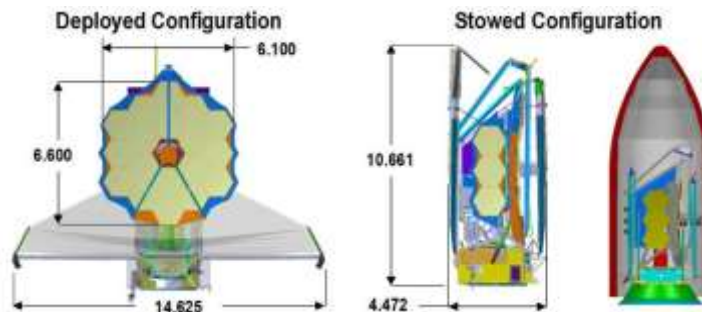




## Launch Vehicles Continue to Drive Design

Similarly, JWST is sized to the Capacities of Ariane 5

	Payload Mass	Payload Volume
Ariane 5	6600 kg (at SE L2)	4.5 m x 15.5 m
James Webb Space Telescope	6530 kg (at SE L2)	4.47 m x 10.66 m



And now the **FUTURE .....**

**A Heavy Lift Launch Vehicle  
would be a Disruptive  
Capability which would offers  
the potential for completely new  
Mission Concepts**

www.nasa.gov

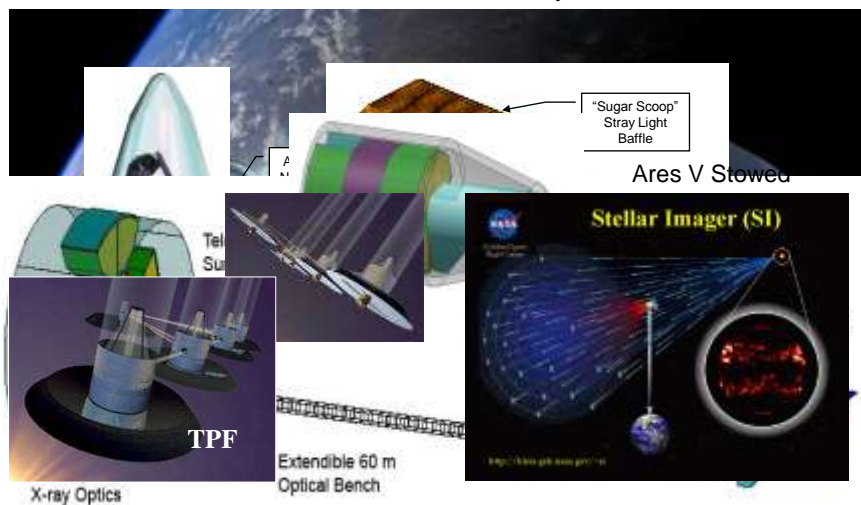




## SLS Changes Paradigms

SLS Mass & Volume enable entirely new Mission Architectures:

- 8 meter class Monolithic UV/Visible Observatory





**And now for something  
completely different ....**

## **Giant Telescopes without mirrors**



### **MOIRE 20 meter Diffractive Telescope**

#### **Design Reference Mission Performance Goals**

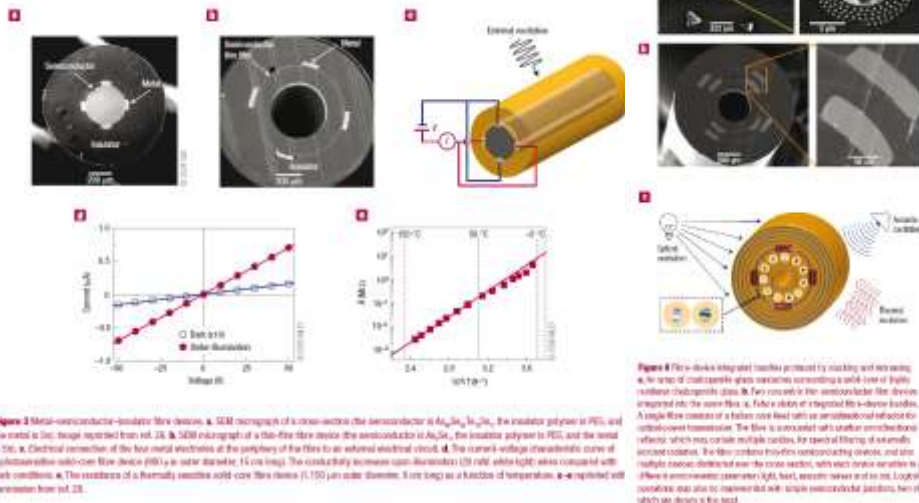
- Persistence – 24/7
- Missile launch detection & vehicle tracking
- Ground Sample Distance -- ~ 1m
- Visible/IR Video @ > 1 Hz
- Field of View > 100 sq km
- Field of Regard – 15,000 km by 15,000 km (without slewing)
- < \$500M/copy (after R&D)



Distribution Statement "A" (Approved for Public Release, Distribution Unlimited). DISTAR case 17534 .



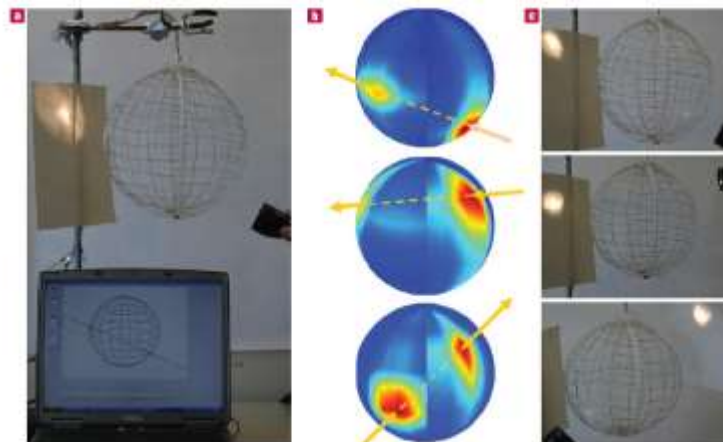
## Consider what you could do with Multi-Spectral Fiber Detectors



Abouraddy, et al., "Towards multimaterial multifunctional fibres that see, hear, sense and communicate", Nature Materials, Vol 6, pp.336, May 2007.



## Computed Axial Tomography Astronomy (Astro-CAT)



Abouraddy, et al., "Large-scale optical-field measurements with geometric fibre constructs", Nature Materials, Vol 5, pp.532, July 2006.



**Any Question?**

